SUDBURY ENVIRONMENTAL STUDY

AN ANALYSIS OF THE IMPACT OF SMELTER EMISSIONS ON ATMOSPHERIC DRY DEPOSITION IN THE SUDBURY AREA: SUDBURY ENVIRONMENTAL STUDY AIRBORNE PARTICULATE MATTER NETWORK RESULTS.

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Minister

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Deputy Minister

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SYNOPSIS

The main objectives of the work described in this report were to determine (1) the removal efficiency of the emissions from the Sudbury INCO and Falconbridge smelters by the process of atmospheric dry deposition, and (2) the impact of smelting activities on the dry deposition of gaseous and particulate sulfur, as well as a number of particulate metal constituents, in the Sudbury area.[1] The scavenging of smelter emissions by precipitation, and the corresponding effects on the wet deposition field around Sudbury, are discussed in two companion reports.[2,3]

Direct measurements of atmospheric dry deposition are extremely difficult, and no methods presently which exist are suitable for routine field use. An alternative, commonly-used approach has been to determine the ambient concentration of the particular substance of interest (be it in the gaseous or particulate form), and then to estimate the deposition flux from the product of concentration and a "deposition velocity" (the magnitude of which can be determined, although for some substances there are large uncertainties in this value). This approach was taken in the present report.

The results presented here are based on almost two years of ambient concentration monitoring for sulfur dioxide, particulate sulfates and

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1. The report also discusses the impact of smelting activities on the ambient concentrations of a number of trace metals in the Sudbury area.
2. Air Resources Branch Report ARB-05-82-ARSP, "An Analysis of the Impact of Smelter Emissions on Precipitation Quality and Wet Deposition in the Sudbury Area: Sudbury Environmental Study Event Precipitation Network Results".
3. Air Resources Branch Report ARB-04-82-ARSP, "Precipitation Quality and Wet Deposition in the Sudbury Basin: Sudbury Environmental Study Cumulative Precipitation Network Results".

trace metals in the Sudbury area (from July, 1978 to May, 1980), together with supporting measurements, both at ground-level and within the INCO and Falconbridge Smelter plumes, of particle size distributions of sulfates and various metals (the latter measurements were needed to calculate deposition velocities for these substances). A detailed meteorological analysis, together with ambient air concentration information, allowed a distinction to be made between samplers impacted by smelter emissions and those exposed to background air, and resulted in the following conclusions:

(1) Dry deposition is a relatively inefficient removal mechanism for plume sulfur dioxide and other substances present predominantly in the submicron particle size range (i.e. SO_4, Pb, Zn, Cd); less than 5% of the emissions are deposited within 40 Km of the smelter sources. On the other hand, a higher proportion of the particles in the coarse size range (containing most of the airborne Fe, Al and Ni) - up to about 50% (long-term average) - can be deposited within this same distance.[4]

(2) During the study period, the smelter contribution to the total dry deposition within 40 Km was greatest for sulfur (primarily due to SO_2) and nickel, making up 27% and 78% of the total respectively for INCO, and 23% and 40% for Falconbridge. The contribution of the other metals examined (Fe, Pb, Zn, Cd and Al) was generally less than 20%. Due to sampling problems, the corresponding figures could not be derived for copper, but results similar to those for nickel are expected, based on the available emission rate and deposition velocity information.

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4. See Tables 18 and 19 in the report.

Table S1 summarizes the results of the present investigation. It should be realized that the information on smelter impact on the dry deposition in the Sudbury area (i.e. the last column in Table S1) applies only to the level of emissions during the study period. Any change in the emission rates is expected to cause a corresponding change in the smelter contribution.

TABLE S1: DRY DEPOSITION OF INCO AND FALCONBRIDGE EMISSIONS WITHIN 40 KM OF THE SOURCE

	Parameter	Average Daily Emissions (kg)	Estimated Dry Deposition ($kg\ d^{-1}$)		% Emission Deposited	Smelter Deposition as % of Total*
			Average Smelter	Average Background		
INCO	SO_2	2.3×10^6	4.0×10^3	10.4×10^3	0.17	28
	SO_4	4.9×10^4	37	400	0.08	8.5
	Total S	1.2×10^6	2.0×10^3	5.3×10^3	0.17	27
	Fe	1.6×10^3	280	1.3×10^3	17	18
	Ni	800	38	11	4.8	78
	Pb	480	0.75	4.1	0.16	15
	Zn	120	0.23	2.5	0.18	8.4
	Al	410	30	520	7.4	5.4
	Cd	37	0.007	0.15	0.02	4.5
Falconbridge	SO_2	2.9×10^5	3.2×10^3	10.4×10^3	1.1	23
	SO_4	4.7×10^3	19	240	0.40	7.4
	Total S	1.3×10^5	1.6×10^3	5.3×10^3	1.1	23
	Fe	100	140	1.1×10^3	140	11
	Ni	14	7.5	11	54	40
	Pb	37	1.4	5.0	3.8	22
	Zn	5.7	0.13	3.2	0.23	3.9
	Al	32	15	420	47	3.5
	Cd	12	0.006	0.15	0.05	3.9

* (INCO Deposition)/(INCO Deposition + Background Deposition) x 100%
or
(Falconbridge Deposition)/(Falconbridge Deposition + Background Deposition) x 100%

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1. INTRODUCTION

As part of the Sudbury Environmental Study (SES), The Air Resources Branch (ARB) was charged with the responsibility of assessing the fate of the pollutants emitted by the INCO and Falconbridge smelters. An airborne particulate matter (APM) monitoring network was set up using high volume (HiVol) samplers, and occasionally Andersen impactors, in the Sudbury area in mid-1977. In the first year, the emphasis was to evaluate sampling methods and site suitability. Not until mid-1978 was the final 8-site HiVol network finalized and operational.

In this report, the historical development of the APM network is presented together with a brief description of the methodologies employed. The focus of the data analysis is on the evaluation of the relative contribution of the local smelters, and other more distant sources, to dry deposition in the Sudbury area; a limited discussion of the impact of the smelters on local air quality (especially with regard to sulfates and trace metals) is also included.

In this account, only the most pertinent results are summarized in the Tables. Details are given in the Supplementary Volume which is available from the Air Resources Branch upon request.

2. NETWORK DESCRIPTION

2.1 SES HiVol Sampling Network

2.1.1 . Historical Developments

The Sudbury Environmental Study HiVol air sampling program operated from May 1977 until May 1980. Throughout its course, both the objectives and methods of the program changed. A summary of the history of the HiVol program is given in Table 2.

The HiVol sampling program began in May, 1977. Two stations were operated at that time, at Ash Street and Burwash. Table 1 and Figure 1 indicate the location of these stations, as well as other stations discussed later.

In July 1977, and again in September 1977, extra stations were added (Lake Panache and Hanmer respectively). Throughout this period, the objective of the sampling was to evaluate the feasibility of determining the ambient concentration of different sulfur species in the Sudbury area. The method of Leahy et al. (1) was modified and adapted for this purpose. It required the selective extraction of sulfuric acid (H_2SO_4), bisulfates (HSO_4) and total water soluble sulfates (SO_4) from exposed HiVol filters.

The sampling was carried out on a 24-hour basis (0800 to 0800 LST) on Tuesdays, Thursdays and Sundays. Gelman Spectro Grade A glass fibre filters were used as the sampling medium.

Initial results and additional developmental work in September 1977 indicated that sulfate speciation was not successful and should be discontinued. Furthermore, there was evidence indicating that glass fibre filters were not suitable for SO_4 measurements due to artifact SO_4 formation; hence, as of early 1978, Whatman 41 filters were used.

Several modifications were initiated from early 1978 until June 1978, i.e. in late April 1978, sampling for SO_2 was added by using Schleicher and Schuell filters impregnated with potassium carbonate and glycerol, downstream of a Tissuquartz particulate filter. In late-May 1978, another station was added at Happy Valley.

In early July of 1978, the HiVol sampling program was re-organized to reflect new objectives. It consisted of eight samplers operating from 0000 to 2400 hours, three days per week, with the purpose of measuring ambient air concentrations of SO_4, NO_3 and several major metals emitted from local smelter operations. Data collected from July of 1978 to May of 1980 were used in this report for the determination of dry deposition in the Sudbury area.

2.1.2 Objectives

The objectives of the SES HiVol Sampling Program were three fold:

(1) To quantify the contribution of local smelter emissions to the dry deposition field in the Sudbury area.

(2) To obtain air quality data on potentially toxic pollutants in the Sudbury area.

(3) To provide data for the verification of computer models developed to assess the fate of locally emitted pollutants.

All three objectives are related to the general objectives of the Sudbury Environmental Study.

2.1.3 Network Design and Operation

Initially, a theoretical network designed to evaluate local source impact was proposed on the basis of long-term meteorological data and mathematical modeling. Due to constraints of site availability and resources, the final network consisted of eight sampling sites (up to a distance of 50 Km from the source). Six of the locations were in the south and southeast quadrants of the two smelter sources and they were downwind of the smelter sources characterized by one of the more dominant wind directions. One of the remaining two sites, Panache, was located in the southwest quadrant as a background monitoring site. The other one, Ash St., within the city of Sudbury, was located to measure both the effects of smelter emissions and urban activities on local air quality. The site location information is given in Table 1 and Figure 1.

The General Metal Works Model GMWL 2000H High Volume Air Samping System was the basic instrument used in this program. A three-day per week schedule was chosen with Sundays, Tuesdays and Thursdays as the principal sampling days. Twenty-four hour sampling was done from 0000 to 2400 hours EST. For all the data reported here, Whatman 41 cellulose filters were used as the filter medium because of their low trace metal background and absence of artifact sulfate formation (2).

The exposed filters were sent to the Laboratory Services Branch (LSB) of the Ministry of the Environment in Toronto for chemical analysis. All samples were analyzed for SO_4, NO_3 and NH_4 upon submission; however, only the Ash St. and Panache filters were analyzed for trace metals at the same time. Filters from the remaining six stations were stored at LSB until the HiVol stratification scheme (see section 3) was completed, and a list of filters requiring metal analysis was forwarded to LSB.

At the beginning of the network operation, SO_4 and NO_3 were analyzed by the autoanalyzer technique, and trace metals by flame atomic absorption. As of April 1979, SO_4 and NO_3 were analyzed by ion-chromatography, NH_4 by the phenate-hypochloride method, and trace metals by flameless AA. These techniques are summarized in Table 3. Due to potential Cu contamination from the HiVol motor exhaust (3), values reported for this species should be used only qualitatively.

During the two years of sampling, there were periods of shutdowns and/or labor strikes at both INCO and Falconbridge. These atypical smelter operating conditions are given in Table 4.

The dry deposition rate is inferred from the HiVol results using the relationship:

$$D = V_d C$$

where D = dry deposition rate per unit area (in mass time^{-1} area^{-1} unit)

V_d = the deposition velocity (see ref. 4, usually in cm s^{-1} unit)

and C = average ambient concentration (usually in ug m^{-3} unit)

Deposition velocity (V_d) is a function of particle size (5). For this reason, particle sizing experiments with Andersen Mark II Samplers at ground level and plume level were carried out to define V_d for background and stack constituents. Details of the experiments are described for the airborne work elsewhere (6,7), and for ground level work in Appendix 1. The recommended deposition velocities however, have been summarized in Table 5. Details on how these values were obtained from the experimentally measured particle diameters, and V_d - diameter relationships given by Dennison et al. (7), are also described in Appendix 1.

3. SAMPLE STRATIFICATION

Due to the large number of samples collected and the high costs associated with chemical analyses for many parameters, it was deemed necessary to stratify the HiVol filters. In the following sections some pertinent information will be given regarding the sample stratification scheme for chemical analysis and the meteorological stratification scheme for deposition analysis purposes.

3.1. HiVol Sample Stratification Scheme

The HiVol stratification scheme was implemented as a method of reducing the number of HiVol filters requiring full chemical analyses, while still allowing the objectives of the program to be fulfilled. The method was designed to identify all filter samples which were potentially affected by the local smelter emissions.

On each of the HiVol sampling days, a map of the Sudbury area showing measured wind directions and SO_2 concentrations observed at continuous monitoring stations operated by the Northeastern Region was prepared, to assess which of the HiVol stations had been affected by the plume. Additional information from visual plume observations (carried out daily by the SES technical staff), as well as pilot balloon data (9), was used to supplement the above data whenever possible. Samples identified as being potentially influenced by smelter emissions were then sent to LSB for trace metal analysis. Further details of the sample stratification scheme are given in Appendix 2.

3.2 Meteorological Data Stratification Scheme

In order to properly assess air quality and relative dry deposition rates due to pollutants generated locally and carried into the region from distant sources, it was necessary to define and classify the samples as to whether or not they have been potentially affected by the local source(s).

The plume sector analysis approach was very similar to that used in the analysis of precipitation samples reported earlier (10). Upper wind information from the MOE tower (114 m) and lower level wind information reported by the Atmospheric Environment Service were extracted and stored in a computer. For each sampling day, plots of the wind direction, and ambient SO_4 and Ni concentrations determined from HiVol sample analysis, were generated by the computer. Using the wind directions as a guide, potential plume sectors were established. For convenience, the plume sector is defined to include all samples which were downwind of the source, as measured by the upper and lower winds, for at least one hour of the sampling period. Usually, elevated SO_4 and Ni concentrations were also observed downwind of the sources, i.e. INCO and Falconbridge. There were occasionally cases for which the assignment of the plume sector was not obvious, and for these a subjective judgement had to be made. For instance, it was observed that in some cases, SO_4 and Ni concentrations immediately upwind of the source were highly elevated. These samples were classified as plume-affected, probably due to plume meandering, if the concentrations of other smelter -related parameters were also found to be elevated.

In this way, samples were labelled as background , INCO - affected, Falconbridge -affected, and both INCO and Falconbridge - affected. The relevant meteorological data are summarized in Section 1 of the Supplementary Volume.

3.3 Data Screening

Before analysis, data were screened by the following procedures:

1. All samples obtained at flow rates outside of 1400 to 2600 m^3/day (approximately 34 to 64 cfm.) were discarded.

2. Data corresponding to the upper 2% concentration range were singled out initially as outliers. The daily areal concentration pattern was carefully examined, to help confirm validity before retaining any of these values in the data base for final analysis.

4. DATA PRESENTATION

4.1 Introduction

Data from all the stations for the two year operational period are given in Section 2 of the Supplementary Volume. In each case, air volume (m^3) and concentration data (ug m^{-3}) for the various parameters are listed. At four locations, SO_2 data were obtained from Northestern continuous monitors. However, those outside of this range are also given for general reference. $N\text{-}NH_4$ was not measured until early 1979. Trace metals that were determined on a regular basis were Fe, Ni, Cu, Pb, Zn, Cd and Al. Cu and Al data should only be used on a qualitative basis. The former suffered from HiVol motor exhaust contamination, therefore representing an upper limit of smelter impact. The latter represents an underestimate because of analytical difficulties. Some other trace metals, were also analyzed on an occasional basis, to get a feel for their ambient concentration, and they are also given in Section 2 of the Supplementary Volume.

4.2 Statistics

A statistical summary of the two years data from all stations is compiled in Table 6. Altogether, there were 1675 samples that fell within this flow volume range. Less $S0_2$ data are available, i.e. 611 readings, because $S0_2$ monitors were only available at four of the eight HiVol stations. Due to the fact that some concentrations were reported as zero,

geometric means were calculated by replacing zeros with values corresponding to one-half of the detection limits. It can be seen from the range that concentration varied a great deal. The geometric mean concentrations (ug m^{-3}) are : SO_2 = 12.7, SO_4 = 2.6, N-NO_3 = 0.16, N-NH_4 = 0.54, Fe = 0.29, Ni = 0.005, Cu = 0.29 (including HiVol exhaust contribution), Pb = 0.04, Zn = 0.02, Cd = 0.001, Al = 0.10 (lower limit), Mn = 0.003 and Mg = 0.73. The corresponding statistics for individual stations are given in Table 7 and Section 3 of the Supplementary Volume.

4.3 Correlation and Regression Analysis

Table 8 gives the linear correlation coefficients for the various measured parameters. Only results that are statistically significant at the 99% confidence level are listed. The top entry corresponds to the coefficient and the bottom entry the number of data pairs.

It is of interest to note that even though SO_2 and SO_4 correlate, the coefficient is low, perhaps indicating that the latter has a large contribution from long range transport. NH_4 and SO_4 correlate highly, suggesting that they are chemically associated. Some of the other parameter pairs with high correlations are Fe and Al, Fe and Mg, Mn and Mg, Al and Mn, as well as Al and Mg, can be attributed to a significant soil contribution. The high correlation for Fe and Ni reflects the smelter contribution of both elements. The high correlations for SO_4 and Mn may be linked with catalytic oxidation of SO_2 by Mn to form SO_4; however this is expected to be important only under high humidity conditions. The high correlation for NH_4 and Mn may be a result of the fact that NH_4 and SO_4

are highly correlated. The high correlation between NO_3 and Mn is not easily explainable.

The corresponding linear regression coefficients for parameter pairs X and Y (A,B, of $Y = \underline{A} + \underline{B}X$; Y and X in units of ug m^{-3}) are summarized in Table 9.

5. DATA ANALYSIS AND DISCUSSION

The two - year HiVol data were further analyzed to determine the following:

a. Typical ambient concentrations due to background air, and local stack emissions.

b. Dependence of plume constituent concentrations on distance from the source.

c. Percentage of Sudbury source emissions deposited in the area through dry mechanisms.

d. Relative dry deposition due to the local and background sources.

5.1 Contribution of Local Sources to Particulate Concentrations

Following the sector analysis method discussed earlier in Section 3.2, concentration data were grouped according to whether they corresponded to background samples, or samples under the plume shadow of INCO and/or Falconbridge.

All the data, except Cu, are summarized in Tables 10 and 11, for background together with the INCO or Falconbridge influence respectively. In both Tables, the daily average background and plume concentrations were first calculated. The individual event values are reported in Section 3 of the Supplementary Volume. These daily areal averages were then further averaged to obtain the concentrations and standard deviations reported in columns 2 and 3, and 4 and 5 respectively in Tables 10 and 11. The average and standard deviation of the

background and plume-affected data were subjected to the student-t test and the results are summarized in the last column of Tables 10 and 11. Essentially, all the plume concentrations show statisically significant differences from those of the background. The data for Cu are only included to show that the smelter contribution of this trace metal is quite large, since it can be detected in spite of the HiVol exhaust contamination, which is known to be significant. In the case of INCO, it is surprising that NO_3 is also significantly higher in the plume shadow, as there is little NO_x emitted from the source (6, 7, 11). One speculation may be that the products of automobile NO_x emissions from the city of Sudbury are being measured together with the plume constituents downwind of the source. Ratios listed in column 6 are quite informative showing the relative magnitude of the plume vs. background concentrations. The very high SO_2 and Ni ratios are consistent with nickel smelter sources.

5.2 Dependence of Plume Constituent Concentrations on Distance from the Emission Source

As in the analysis of the event precipitation data (12), the plume sector additional concentrations over background (hereafter referred to as additional concentrations) were plotted according to the distance intervals between the sampling stations and the source. These additional concentrations due to the local sources were not calculated simply by subtracting mean background concentration from mean plume concentration. On each sampling day, the average daily background concentration was calculated. This average background value was

subtracted from each one of the plume-affected samples (in the plume sector) individually. It is from these resultant values that the grouped data were synthesized. Data were grouped conveniently according to the sampler locations. In the case of INCO these were : 4 Km (representing 0-4Km), 10 Km , 21 Km , 31 Km and 39 Km; in the case of Falconbridge: 1 Km(0-1 Km), 15 Km, 21 Km and 37 Km .

In Tables 12 and 13, the results are partitioned into different sampling distance intervals. Under each group, the number of data points used in the calculations, and the mean concentrations and standard deviations are listed. Note that there are fewer data points farther downwind of the sources.

The rationale for compiling additional concentration data is to establish an empirical relationship between the additional plume concentration and the distance from the source, from which dry deposition calculations can be made.

Four different expressions were used to establish the concentration dependence on distance with both individual data points and grouped data points. There were:

$$(\text{Conc}) = A + B\,R \qquad (1)$$

$$(\text{Conc}) = A + B/R \qquad (2)$$

$$\ln(\text{Conc}) = A + B\,R \qquad (3)$$

$$\ln(R\ \text{Conc}) = A + B\,R \qquad (4)$$

Aside from the larger scatter of the data using individual points resulting in a lower correlation, similar deposition results were obtained by using individual and grouped data points. In the present report, further discussion, including dry deposition estimates, will be based on the grouped data.

Comparing results of grouped data using expressions (1) to (4), it was found that expression (2) in general gave the best fit of the data. All the correlation results are given in Tables 14 to 17. In each table, the first column lists the parameters of interest, and COR corresponds to correlation coefficients. A and B designate regression coefficients A and B in expressions (1) to (4). The high correlations in some cases using expression (4) may be fortuitous because the change in concentration as a function of distance is small and effectively the fit is nothing but ln R + ln constant vs. R.

It should be pointed out that the fits using expression (2) for all INCO parameters (except for Al) are quite good, but they are not so good for parameters NO_3, Pb and Zn in the case of Falconbridge.

5.3 Fraction of INCO and Falconbridge Emissions Dry Deposited (within 40 Km)

Dry deposition estimates of plume constituents can be made by using the corresponding air concentration and deposition velocity according to:

$$F = C \cdot V_d \cdot A_{plume} \qquad (5)$$

where

F = areal dry deposition flux per unit time

C = average additional plume concentration (in ug m^{-3} unit)

V_d = deposition velocity of plume constituents (in cm s^{-1} unit)

and A_{plume} = area defined by plume sector

The values of C used in the calculations below were determined from Equation (2), fitted to grouped additional concentration data. V_d values were determined from airborne particle sizing measurements and have been summarized in Table 5. A long-term average value of V_d equal to 0.3 cm s^{-1} was used for SO_2, as calculated according to the methods recommended by Sheih et al. (13). It should be pointed out that there is considerable uncertainty in the V_d values, especially for SO_4 - see, for example, Lusis and Shenfeld (14). A_{plume} was calculated for INCO and Falconbridge using a sector size of 60.4° and 57.4° respectively, determined for the sampling days as described in Section 3.2.

The fraction of emissions dry-deposited for each substance is the ratio of the dry deposition rate to the emission rate. SO_2 emission data are in general available from in-stack continuous monitor measurements or mass balance calculations for the two sources. In INCO's case, daily figures were available for the 381 m chimney and the Iron Ore Recovery Plant (IORP), but in the case of Falconbridge, data were available only on a monthly basis. Low-level emissions were assumed to be 2% of the smelter stack emissions as suggested by the Northeastern Region (15). Particulate emissions were in turn estimated from the SO_2 data and particulate-to-SO_2 emission ratios (16). The SO_2 emission rates over the period of interest were estimated from data provided by the Northeastern Region and are summarized together with a more detailed description of the calculation method elsewhere (12).

Tables 18 and 19 show the analysis results for dry deposition around the INCO and Falconbridge smelters. The parameters of interest are listed in column 1, the emissions data in column 3. The quantity dry-deposited was calculated using expressions (2) and (5), with grouped data. As pointed out earlier (Section 3.1), samples were stratified before submission to the laboratory for analysis, with only samples having evidence of plume impingement being submitted. This means that the results listed in column 3 correspond to the average deposition during plume impingement days only, and are overestimates for the overall annual average deposition. They therefore must be prorated by the fraction of filters submitted vs. the total filters collected. By doing so, we would then also account for the days when the plume was aloft and there was negligible dry deposition. These correction factors are 68.6% and 62.6% for INCO and Falconbridge respectively. The prorated results are listed under column 6. Column 7 corresponds to the ratio of column 6 to column 4, and shows that the amount of the emissions dry deposited within 40 Km is small for INCO, especially for parameters in the fine particle size range. Coarse particles such as Fe, Ni and Al deposit faster. The results for Fe and Al however are complicated by the fact that these elements also have a significant soil component, i.e. a fraction of the dry-deposited values in column 6, which is difficult to estimate, may have come from windblown dust (although in theory, our procedure of subtracting out "background" concentration should account for this). In the case of Falconbridge, the percentage of emissions deposited is in general higher than that for INCO. This is party due to the lower height of the emissions, but may also be due to a possible interference from INCO emissions in the Falconbridge plume sector on some events.

5.4. Contribution of the Local Sources to Total Dry Deposition (within 40 Km)

Except for SO_2, using the average background concentrations in Tables 10 and 11, and the deposition velocities inferred from sizing experiments made at ground level (see Table 5), background contributions were calculated for the two sources, and are listed under column 8 of Tables 18 and 19. It is felt that the background SO_2 concentrations given in Tables 10 and 11 are artificially low because of limitations of the SO_2 monitors in detecting low concentrations. All the SO_2 data available from the Northestern Region for use in this work were reported in the unit of 10 ppb. This means that, at low levels, concentrations are reported either as zero or as 10 ppb. An SO_2 background concentration of 8 ug m^{-3} based on some measurements at Chalk River (22) was used in our calculations.By comparing columns 6 and 8, the % local source contribution to the total dry deposition out to 40 Km can be calculated. Column 9 gives these results. It is noted that the relative contribution to the total from INCO is higher than that from Falconbridge. It is of interest to point out that farther away from the source, the less the relative contribution of the local source to the total dry deposition. Note that the greatest smelter contributions are for sulfur and nickel although the values for lead and iron are also quite large. In view of the corresponding results for wet deposition (12), and their comparable emission rates and deposition velocities, it is reasonable to expect that the smelter impact on copper dry deposition would be approximately as great as that for nickel.

6. CONCLUSIONS

An airborne particulate matter network was set up in Sudbury with 8 HiVol stations located primarily in the E and SE quadrants up to a radius of 50 Km, to monitor the local air quality and to yield information leading to dry deposition estimates. The latter results were obtained from a knowledge of the ambient air concentrations and particle size distribution data from Andersen Sampling. The two years data (July '78 to May '80) were analyzed. Altogether 1675 HiVol samples were collected during the two study years; however less SO_2 data were collected from continuous monitors because only 4 network stations had the Northeastern Region SO_2 instrumentation.

The following conclusions were reached:

- The geometric mean concentrations (ug m^{-3}) over the two years were found to be: SO_2 = 12.7, SO_4 = 2.6, N-NO_3 = 0.16, N-NH_4 = 0.54, Fe = 0.29, Ni = 0.005, Pb = 0.04, Zn = 0.02, Cd = 0.001, Al = 0.10 (lower limit only), Mn = 0.003 and Mg = 0.73.

- SO_2 and SO_4 did not correlate highly, suggesting that the latter had a large contribution from long range transport. NH_4 and SO_4 correlated highly, suggesting that they were chemically associated.

- It was found that the sector analysis approach, using stratification based on meteorology and chemical information, is quite useful for estimating the contribution of the local smelter sources to ambient air quality. Ground-level concentrations are higher downwind of

the INCO source than those downwind of the Falconbridge source. The parameters showing the greatest difference between plume and background concentrations were SO_2 and Ni.

- Up to a radius of 40 Km from the source, it was found that for SO_2 and metals in the fine particle size range (SO_4, Pb, Zn, Cd), less than 5% of the emissions were deposited. The percentage deposition locally for coarse particles (Fe, Ni, Al) was higher and in the case of Falconbridge, could be as high as 50% or more.

- The smelter contribution to total dry deposition within 40 Km was greatest for sulfur (primarily due to SO_2) and nickel, making up 61% and 78% of the total respectively for INCO, and 36% and 40% for Falconbridge. The contribution of the other metals examined was generally less than 20%. No conclusions were possible for copper, due to sampling problems, but results comparable to nickel are expected, based on emission rate, particle size and deposition velocity information.

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Table I: High Volume Sampling Network Station Locations

Station No.	Station	Elevation	Latitude	Longitude	UTM Easting Northing NORMAL
1	Ash Street	840'	46°29'39"	81°00'38"	499400 5148700 MB 9948
2	Lake Panache	750'	46°16'27"	81°20'42"	473400 5120400 MB 7324
3	McFarlane Lake	775'	46°25'36"	80°57'07"	503600 5141300 NB 0341
4	Burwash	750'	46°15'46"	80°48'48"	514600 5123000 NB 1422
5	Wanup	780'	46° 24'06"	80°50'53"	511700 5138400 NB 1138
6	Happy Valley	925'	46°33'48"	80°48'23"	515000 5156700 NB 1556
7	Markstay	730'	46°29'40"	80°32'10"	535600 5148800 NB 3549
8	Moonlight Beach	810'	46°28'48"	80°54'42"	506900 5146800 NB 0747

Table 2: A Summary of ARB/SES HiVol Sampling Program

PERIOD	STATION	SAMPLING	FILTER MEDIUM	ANALYSIS
1977, May-(0800-0800)*	Ash Street	Particulate	Gelman Spectro Grade A Glass Fiber	$SO_4^=$, H_2SO_4 H_2SO_4
1977, July - (0800-0800)	Ash Street Burwash Lake Panache	Particulat	Spectro Grade A Glass Fibre	$SO_4^=$, HSO_4^-, H_2SO_4 (up to August)
1977, Sept. - (0800-0800)	Ash Street Burwash Lake Panache Hanmer	Particulate	Spectro Grade A	$SO_4^=$, NO_3^-
1978, mid January - (0800-0800)	Ash Street Burwash Lake Panache Hanmer	Particulate	Whatman 41	$SO_4^=$, NO_3^-
1978 late April - (0800-0800)	Ash Street Burwash Lake Panache Hanmer	Particulate SO_2	Tissuquartz QAO S/S Impregnated Filters	$SO_4^=$, NO_3^- SO_2
1978 late May - (0800-0800)	Ash Street Burwash Lake Panache Wanup Happy Valley	Particulate SO_2	Tissuquartz QAO S/S Impregnated Filter	$SO_4^=$, NO_3^- SO_2
1978 late June - (0800-0800)	Ash Street Burwash Lake Panache Happy Valley Wanup McFarlane	Particulate SO_2	Whatman 41 S/S Filters	$SO_4^=$, NO_3^-, Metal, SO_2
1978 July-1980 May (0000-2400)	Ash Street Burwash Happy Valley Markstay McFarlane Moonlight Beach Lake Panache Wanup	Particulate SO_2	Whatman 41 S/S Filters	$SO_4^=$, NO_3^- Metals, SO_2 (Sampling terminated late September, 1978). NH_4 added as of April, 1979

* Sample collection time, local time.

TABLE 3: Summary of Analytical Techniques and Detection Limits

Parameters	Technique	Detection Limit* (ug/m^3)
SO_4	Ion Chromatography+	0.03
$N\text{-}NO_3$	Ion Chromatography+	0.005
$N\text{-}NH_4$	Phenate-hypochloride method	0.008
Fe		0.02
Cu		0.007
Ni		0.002
Pb	Flame Atomic Absorption Spectrometry	0.004
Zn		0.01
Al		0.09
Cd		0.0003
As		0.0004
Se		0.0004
Mn		0.0007
Mg		0.04
SO_2	Continuous Monitor	13.0**

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* Assuming a volume of 2000 m^3/sample except in the case of SO_2 measurements.

** Converted from 5 ppb detection limit.

\+ Technicon Autoanalyzer was used before April, 1979.

TABLE 4: Atypical Smelter Operating Conditions*
(1978-1980)

Time	Industry	Operating Conditions	
		Shutdown	Strike
1978			
July 1 - Aug. 21	Falconbridge	X	
July 17 - Aug. 27	INCO	X	
Sept. 16 - Dec. 31	INCO		X
1979			
Jan. 1 - Jun. 7	INCO		X
Jul. 8 - Jul. 22	Falconbridge	X	

* The unspecified periods correspond to normal operations.

TABLE. 5: SUMMARY OF DEPOSITION VELOCITIES V_d (cm s^{-1})

	Background[+]	Smelter Source[++]
Fe	1.23	2.0
Cu	.49	2.5
Ni	1.3	3.3
Pb	.028	.10
Zn	.024	.04
Mn	.44	1.03
Al	.94	1.00
Cd	.035	.30
Ca	.865	*
Cr	.30	0.20
Mg	1.04	1.30
As	.28	1.08
Se	.030	.045
SO_4	.027	.057
NH_4	.027	.063
NO_3	.020	*

[+] Inferred from particle sizing data obtained at ground level in August /78, April and August /79 and March /80.

[++] Inferred form particle sizing data obtained at plume level in September /79 and March /80.

* Not determined.

TABLE 6: STATISTICAL SUMMARY OF SES HIVOL DATA

HI-VOL SAMPLING ANALYSIS RESULTS

SUDBURY ENVIRONMENT STUDY

THE STATISTICAL TABLE+ALL DATA
(CONCENTRATION)

ALL STATIONS
STATISTICAL PERIOD : 780701-800529

	AIR VOL. (M**3)	(UG/M**3) SO2*	SO4	N-NO3	N-NH4	FE	NI	CU	PB	ZN	CD	AL	AS	SE	MN	MO
SAMPLE SIZE	1675.	611.	1670.	1666.	1232.	1245.	1235.	1246.	1246.	1244.	1236.	854.	11.	10.	399.	223.
MAXIMUM	2568.80	439.73	61.30	8.66	7.110	8.675	0.732	2.386	0.563	0.387	0.032	2.222	0.011	0.010	0.110	2.985
MINIMUM	1401.40	0.50	0.02	0.00	0.004	0.010	0.001	0.003	0.002	0.005	0.000	0.045	0.000	0.000	0.000	0.020
RANGE	1167.40	433.23	61.29	8.66	7.106	8.665	0.731	2.382	0.561	0.382	0.032	2.177	0.011	0.010	0.110	2.885
ARITH. MEAN	1817.06	24.28	4.16	0.31	0.941	0.525	0.021	0.426	0.066	0.037	0.002	0.189	0.003	0.003	0.008	0.139
ARITH. STD. DEV.	193.81	48.63	5.10	0.49	1.031	0.765	0.054	0.378	0.069	0.039	0.003	0.255	0.003	0.003	0.010	0.247
GEOM. MEAN	1804.75	12.65	2.59	0.16	0.548	0.286	0.005	0.286	0.037	0.024	0.001	0.101	0.001	0.002	0.003	0.073
GEOM. STD. DEV.	0.11	1.13	1.03	1.24	1.209	1.141	1.581	0.984	1.285	0.953	1.432	1.101	1.174	1.305	1.453	1.129
1ST QUARTILE	1677.45	6.50	1.50	0.07	0.290	0.143	0.001	0.160	0.020	0.013	0.000	0.043	0.001	0.001	0.001	0.014
2ND QUARTILE	1814.40	3.00	2.50	0.16	0.540	0.299	0.005	0.290	0.044	0.026	0.000	0.102	0.002	0.002	0.005	0.066
3RD QUARTILE	1927.30	29.90	4.99	0.36	1.205	0.610	0.015	0.600	0.090	0.046	0.002	0.231	0.003	0.004	0.010	0.101

***** : INSUFFICIENT DATA

* : DATA FROM CONTINUOUS MONITOR

TABLE 7: SUMMARY OF GEOMETRIC MEAN AMBIENT CONCENTRATION ($\mu g\ m^{-3}$)
(JULY, 1978 - MAY, 1980)

Station	SO_2	SO_4	$N\text{-}NO_3$	$N\text{-}NH_4$	Fe	Ni	Pb	Zn	Cd	Al
Ash St.	24.7	2.9	.22	.64	.62	.02	.10	.04	.001	.16
Burwash	8.1	2.4	.13	.45	.17	.003	.03	.02	.001	.07
Panache	7.3	2.5	.15	.62	.13	.002	.02	.02	<.001	.06
Happy Valley	18.2	2.9	.17	.60	.41	.02	.03	.02	.001	.12
Markstay	-	2.6	.13	.53	.29	.003	.03	.03	.001	.12
McFarlane	-	2.5	.15	.56	.36	.005	.04	.02	<.001	.14
Moonlight Beach	-	2.7	.19	.50	.36	.008	.04	.03	.001	.08
Wanup	-	2.3	.15	.71	.23	.004	.03	.02	<.001	.08

TABLE 3: CORRELATION ANALAYSIS OF SES HIVOL DATA

HI-VOL SAMPLING ANALYSIS RESULTS - SES

LINEAR CORRELATION COEFFICIENT
90% CONFIDENCE LEVEL
(# OF OBSERVATION PTS)

ALL STATIONS

PERIOD : 780701-800531

	SO2*	SO4	NO3	NH4	FE	NI	CU	PB	ZN	CD	AL	AS	SE	MN	MG
SO2*	1.000 611														
SO4	0.166 609	1.000 1670													
NO3		0.321 1646	1.000 1666												
NH4	0.168 444	0.700 1231	0.404 1230	1.000 1232											
FE	0.249 587	0.207 1243	0.092 1241	0.277 942	1.000 1245										
NI	0.312 583	0.168 1233		0.267 933	0.686 1233	1.000 1235									
CU		0.177 1244	0.098 1242	0.268 943	0.388 1245	0.381 1234	1.000 1246								
PB	0.255 568	0.328 1244	0.298 1242	0.384 943	0.296 1244	0.269 1235	0.421 1246	1.000 1246							
ZN	0.227 566	0.319 1242	0.254 1240	0.233 941	0.214 1243	0.196 1233	0.299 1244	0.472 1243	1.000 1244						
CD	0.536 564	0.186 1234			0.148 1235	0.271 1229	0.107 1236	0.348 1236	0.432 1234	1.000 1236					
AL		0.243 654		0.256 812	0.654 850	0.165 641	0.239 851	0.174 850	0.196 850		1.000 854				
AS												1.000 11			
SE	0.834 9				0.816 10		0.883 10					0.949 10	1.000 10		
MN		0.546 397	0.510 396	0.558 185	0.467 399			0.384 399	0.241 399		0.624 189			1.000 399	
MG			0.217 221	0.292 127	0.770 223				0.191 223		0.648 78	0.854 10		0.627 147	1.000 223

* -- DATA FROM CONTINUOUS MONITOR

TABLE 9: REGRESSION ANALYSIS OF SES HIVOL DATA

HI-VOL SAMPLING ANALYSIS RESULTS - SES

TWO VARIABLES OF THE LINEAR REGRESSION
(A & B)

ALL STATIONS

PERIOD : 780701-800531

	SO2*	SO4	NO3	NH4	FE	NI	CU	PB	ZN	CD	AL	AS	SE	MN	HG
SO2*	0.0														
	1.000														
SO4	3.963	0.0													
	0.817	1.000													
NO3		0.181	0.0												
		0.031	1.000												
NH4	0.862	0.346	0.693	0.0											
	0.884	0.135	0.798	1.000											
FE	0.433	0.375	0.479	0.345	0.0										
	0.005	0.037	0.159	0.222	1.000										
NI		0.012		0.010	-.003	0.0									
		0.002		0.017	0.044	1.000									
CU		0.263	0.442	0.345	0.350	0.378	0.0								
		0.015	0.082	0.102	0.145	2.314	1.000								
PB		0.045	0.053	0.046	0.052	0.060	0.033	0.0							
		0.005	0.047	0.020	0.027	0.333	0.079	1.000							
ZN		0.025	0.030	0.029	0.031	0.034	0.023	0.019	0.0						
		0.003	0.023	0.010	0.011	0.138	0.032	0.270	1.000						
CD					0.001	0.001	0.001			0.0					
					0.001	0.015	0.001			1.000					
AL		0.125		0.130	0.071	0.172	0.118	0.146	0.139		0.0				
		0.015		0.067	0.216	0.642	0.159	0.658	1.337		1.000				
AS												0.0			
												1.000			
SE					0.001		-.002					-.001	0.0		
					0.003		0.013					2.102	1.000		
MN		0.003	0.004	0.004	0.004			0.004	0.005		0.004			0.0	
		0.001	0.011	0.005	0.007			0.041	0.052		0.021			1.000	
HG			0.093	0.108	0.010				0.008		0.032	0.009		0.032	0.0
			0.136	0.053	0.231				1.442		0.308	62.00		12.99	1.000

* -- DATA FROM CONTINUOUS MONITOR

TABLE 10: RELATIVE BACKGROUND AND INCO PLUME CONCENTRATIONS (UG/M**3)

PARA	BK MN (A)	PM MN (B)	BK SD	PM SD	RATIO (B/A)	NN	T-T
SO2	1.790	37.264	4.185	36.165	20.822	65	7.762
SO4	3.411	5.080	3.657	4.607	1.489	116	9.103
NNO3	0.226	0.311	0.267	0.383	1.376	116	6.220
NNH4	0.720	1.090	0.752	1.023	1.514	108	7.195
FE	0.239	0.698	0.262	0.686	2.928	97	8.037
NI	0.002	0.052	0.003	0.051	25.407	91	9.429
CU	0.314	0.533	0.212	0.297	1.696	97	6.980
PB	0.034	0.078	0.033	0.063	2.319	97	8.649
ZN	0.024	0.042	0.023	0.036	1.747	96	5.283
CD	0.001	0.002	0.002	0.002	1.950	95	4.734
AL	0.128	0.182	0.145	0.175	1.418	95	4.130

PARA: PARAMETER
BK: BACKGROUND
MN: MEAN
PM: PLUME
SD: STANDARD DEVIATION
NN: NUMBER OF DATA PAIRS
T-T: STUDENT-T STATISTICS

TABLE 11: RELATIVE BACKGROUND AND FALCONBRIDGE PLUME CONCENTRATION(UG/M**3)

PARA	BK MN (A)	PM MN (B)	BK SD	PM SD	RATIO (B/A)	NN	T-T
SO2	4.211	74.044	10.200	114.620	17.581	49	4.236
SO4	2.415	3.432	2.078	2.459	1.421	133	9.500
NNO3	0.167	0.229	0.213	0.277	1.226	132	4.572
NNH4	0.499	0.692	0.476	0.649	1.388	94	5.274
FE	0.205	0.472	0.164	0.395	2.297	107	7.288
NI	0.002	0.014	0.004	0.018	7.167	107	7.146
CU	0.306	0.387	0.195	0.288	1.264	109	2.621
PB	0.041	0.070	0.037	0.062	1.736	108	5.848
ZN	0.031	0.039	0.028	0.032	1.267	108	4.485
CD	0.001	0.002	0.003	0.003	1.882	108	6.180
AL	0.102	0.148	0.110	0.139	1.444	66	4.039

PARA: PARAMETER
BK: BACKGROUND
MN: MEAN
PM: PLUME
SD: STANDARD DEVIATION
NN: NUMBER OF DATA PAIRS
T-T: STUDENT-T STATISTICS

TABLE 12. ARC MEAN ADDITIONAL CONCENTRATION(UG/M**3) & STANDARD DEVIATION DUE TO INCO PLUME

	(4.) KM			(10.) KM			(21.) KM			(31.) KM			(39.) KM		
PM	NN	CONC	STDV	NN	CONC	STDV	NN	CONC	STDV	NN	CONC	STDV	NN	CONC	STDV
SO2	50	47.6122	38.4518	0			17	33.9508	34.3495	27	17.4311	34.9073	0		
SO4	73	2.2516	2.7120	76	1.6777	2.2303	48	1.2907	1.8245	69	1.2873	2.2060	19	0.9925	1.0156
NNO3	73	0.1514	0.1867	75	0.0642	0.1326	47	0.0951	0.1349	69	0.0106	0.0659	19	-0.0333	0.0723
NH4	67	0.8084	0.9973	73	0.3801	0.5152	48	0.4382	0.4814	69	0.1256	0.3759	18	0.1378	0.2693
FE	69	1.2249	1.7157	64	0.4473	0.3890	41	0.3518	0.4047	54	0.0565	0.1863	16	0.2678	0.3322
NI	65	0.1238	0.1456	63	0.0452	0.0504	41	0.0231	0.0264	51	0.0174	0.0295	15	0.0096	0.0172
PB	69	0.1007	0.0692	64	0.0276	0.0368	41	0.0188	0.0319	51	0.0084	0.0248	14	0.0050	0.0191
ZN	68	0.0421	0.0497	64	0.0126	0.0200	41	0.0122	0.0212	54	0.0035	0.0212	16	0.0169	0.0185
CD	68	0.0027	0.0043	64	0.0007	0.0016	41	0.0005	0.0009	52	0.0001	0.0009	16	0.0005	0.0006
AL	68	0.1194	0.2155	63	0.0667	0.1476	40	0.0843	0.1392	54	-0.0105	0.0978	14	0.0956	0.1619

PM: PARAMETER
NN: NUMBER OF DATA POINTS
CONC: MEAN CONCENTRATION
STDV: STANDARD DEVIATION

TABLE 13: ARC MEAN ADDITIONAL CONCENTRATION(UG/M**3) & STANDARD DEVIATION DUE TO FALCONBRIDGE PLUME

	(1.) KM			(15.) KM			(21.) KM			(37.) KM		
PM	NN	CONC	STDV	NN	CONC	STDV	NN	CONC	STDV	NN	CONC	STDV
SO2	36	87.4966	130.79	14	28.4305	28.8708	0			5	20.2680	22.5558
SO4	72	1.7877	2.5150	64	0.9798	1.6865	123	0.6960	1.1111	31	0.6398	1.0867
NNO3	71	0.0579	0.1220	63	0.0652	0.1312	123	0.0427	0.1364	30	-0.0125	0.0556
NNH4	52	0.2623	0.4261	43	0.1240	0.4760	86	0.1553	0.3396	24	0.0762	0.3832
FE	56	0.5223	0.6725	50	0.3096	0.2907	104	0.1326	0.3297	30	0.0449	0.1534
NI	58	0.0363	0.0424	47	0.0089	0.0118	106	0.0039	0.0086	30	0.0025	0.0125
PB	57	0.0168	0.0405	50	0.0664	0.0768	104	0.0185	0.0463	30	0.0150	0.0454
ZN	59	0.0104	0.0380	50	0.0141	0.0241	106	0.0055	0.0227	28	0.0031	0.0191
CD	57	0.0030	0.0043	50	0.0008	0.0023	105	0.0005	0.0015	29	0.0002	0.0017
AL	38	0.0702	0.0944	27	0.0418	0.1044	63	0.0342	0.1142	17	0.0263	0.0581

PM: PARAMETER
NN: NUMBER OF DATA POINTS
CONC: MEAN CONCENTRATION
STDV: STANDARD DEVIATION

TABLE 14: CORRELATION AND REGRESSION COEFFICIENTS FOR ADDITIONAL INCO PLUME CONCENTRATION AND DISTANCE USING INDIVIDUAL DATA POINTS

$CONC = A1 + B1 * R$ (1)
$CONC = A2 + B2 / R$ (2)
$\ln (CONC) = A3 + B3 * R$ (3)
$\ln (R * CONC) = A4 + B4 * R$ (4)

PARAMETER	CORRELATION COEFFICIENT				REGRESSION COEFFICIENT							
	COR1	COR2	COR3	COR4	A1	B1	A2	B2	A3	B3	A4	B4
SO_2	-0.34	0.32	-0.55	-0.02	52.4373	-1.0765	19.1833	114.6072	3.9145	-0.0816	5.0218	-0.0029
SO_4	-0.17	0.18	-0.14	0.31	2.1794	-0.0323	1.1126	4.6810	-0.1246	-0.0201	1.2707	0.0470
NNO_3	-0.35	0.35	-0.24	0.03	0.1471	-0.0043	0.0099	0.5745	-3.1323	-0.0606	-1.7392	0.0065
NNH_4	-0.33	0.35	-0.27	0.11	0.7458	-0.0188	0.1252	2.7452	-0.9971	-0.0584	-1.5791	0.0191
Fe	-0.35	0.42	-0.47	-0.12	1.0793	-0.0315	-0.0022	4.8798	-0.4167	-0.0869	0.9567	-0.0190
Ni	-0.39	0.47	-0.48	-0.11	0.1074	-0.0032	-0.0013	0.4967	-2.5870	-0.0861	-1.2074	-0.0182
Pb	-0.52	0.64	-0.51	-0.04	0.0853	-0.0027	-0.0072	0.4237	-2.7467	-0.0728	-1.3791	-0.0043
Zn	-0.31	0.41	-0.33	0.28	0.0346	-0.0009	0.0010	0.1596	-4.0802	-0.0374	-2.7040	0.0304
Cd	-0.29	0.37	-0.28	0.37	0.0022	-0.0001	-0.0002	0.0111	-7.0576	-0.0291	-5.6816	0.0388
Al	-0.20	0.21	-0.27	0.11	0.1163	-0.0029	0.0245	0.3890	-2.9477	-0.0492	-1.5791	0.0191

TABLE 15: CORRELATION AND REGRESSION COEFFICIENTS FOR ADDITIONAL INCO PLUME CONCENTRATION AND DISTANCE USING GROUPED DATA POINTS

$CONC = A1 + B1 * R$ (1)
$CONC = A2 + B2 / R$ (2)
$\ln(CONC) = A3 + B3 * R$ (3)
$\ln(R * CONC) = A4 + B4 * R$ (4)

PARAMETER	CORRELATION COEFFICIENT				REGRESSION COEFFICIENT							
	COR1	COR2	COR3	COR4	A1	B1	A2	B2	A3	B3	A4	B4
SO_2	-0.98	0.87	-0.94	0.84	53.2397	-1.0844	21.0965	108.2354	4.0757	-0.0354	5.2385	0.0428
SO_4	-0.93	0.97	-0.95	0.94	2.1545	-0.0312	1.0418	5.0290	0.7964	-0.0205	2.2687	0.0411
NNO_3	-0.91	0.82	-0.83	-0.62	0.1526	-0.0045	0.0001	0.6308	0.1850	-0.2283	0.2590	-0.0475
NNH_4	-0.88	0.93	-0.92	0.38	0.7352	-0.0170	0.1269	2.7560	-0.1507	-0.0506	1.3215	0.0111
Fe	-0.79	0.97	-0.73	0.11	0.9823	-0.0244	0.0464	4.6460	0.0172	-0.0564	1.4894	0.0052
Ni	-0.84	1.00	-0.96	-0.40	0.1006	-0.0027	-0.0016	0.4982	-2.1570	-0.0654	-0.6847	-0.0038
Pb	-0.81	0.99	-0.97	0.76	0.0785	-0.0022	-0.0060	0.4180	-2.3566	-0.0778	-0.8844	-0.0161
Zn	-0.61	0.91	-0.55	0.56	0.0305	-0.0006	0.0045	0.1418	-3.6297	-0.0336	-2.1575	0.0281
Cd	-0.72	0.97	-0.69	0.10	0.0020	-0.0001	-0.0001	0.0104	-6.3360	-0.0564	-4.8638	0.0053
Al	-0.40	0.55	-0.39	0.18	0.1001	-0.0014	0.0444	0.2935	-1.9294	-0.1097	-0.7432	0.0181

TABLE 16: CORRELATION AND REGRESSION COEFFICIENTS FOR ADDITIONAL FALCONBRIDGE PLUME CONCENTRATION AND DISTANCE USING INDIVIDUAL DATA POINTS

CONC = A1 + B1 * R (1)
CONC = A2 + B2 / R (2)
ln (CONC) = A3 + B3 * R (3)
ln (R * CONC) = A4 + B4 * R (4)

PARAMETER	CORRELATION COEFFICIENT				REGRESSION COEFFICIENT							
	COR1	COR2	COR3	COR4	A1	B1	A2	B2	A3	B3	A4	B4
SO_2	-0.24	0.27	-0.05	0.44	34.8727	-2.3637	22.5852	64.9354	2.6397	-0.0108	2.7173	0.1092
SO_4	-0.24	0.25	-0.18	0.34	1.6582	-0.0386	0.7157	1.0764	-0.5265	-0.0374	-0.1309	0.0770
NNO_3	-0.14	0.06	-0.16	0.36	0.0724	-0.0016	0.0404	0.0184	-3.7772	-0.0327	-3.3854	0.0822
NNH_4	-0.14	0.14	-0.18	0.34	0.2501	-0.0051	0.1272	0.1354	-2.5811	-0.0377	-2.1836	0.0754
Fe	-0.36	0.34	-0.45	0.05	0.5050	-0.0150	0.1465	0.3795	-1.2212	-0.1003	-0.7738	0.0102
Ni	-0.46	0.51	-0.59	0.43	0.0311	-0.0011	0.0033	0.0331	-4.0495	-0.0670	-3.6258	0.0443
Pb	-0.04	-0.10	-0.04	0.58	0.0308	-0.0002	0.0314	-0.0138	-4.2939	-0.0054	-3.8042	0.1054
Zn	-0.09	0.05	-0.06	0.56	0.0121	-0.0002	0.0073	0.0032	-5.0691	-0.0092	-4.6578	0.1036
Cd	-0.34	0.37	-0.25	0.39	0.0026	-0.0001	0.0004	0.0026	-6.8202	-0.0416	-6.3874	0.0699
Al	-0.15	0.15	-0.23	0.48	0.0669	-0.0014	0.0330	0.0373	-3.4190	-0.0338	-3.0504	0.0801

TABLE 17: CORRELATION AND REGRESSION COEFFICIENTS FOR ADDITIONAL FALCONBRIDGE PLUME CONCENTRATION AND DISTANCE USING GROUPED DATA POINTS

CONC = A1 + B1 * R (1)
CONC = A2 + B2 / R (2)
ln (CONC) = A3 + B3 * R (3)
ln (R * CONC) = A4 + B4 * R (4)

PARAMETER	CORRELATION COEFFICIENT				REGRESSION COEFFICIENT							
	COR1	COR2	COR3	COR4	A1	B1	A2	B2	A3	B3	A4	B4
SO_2	-0.86	1.00	-0.91	0.92	76.0355	-1.7342	21.1796	66.4320	4.2874	-0.0384	4.7149	0.0567
SO_4	-0.89	0.97	-0.92	0.88	1.6121	-0.0317	0.7192	1.0746	0.4722	-0.0289	1.0120	0.0685
NNO_3	-0.87	0.40	-0.84	0.08	0.0762	-0.0021	0.0299	0.0296	-0.5836	-0.2421	-1.4965	0.0084
NNH_4	-0.91	0.92	-0.94	0.83	0.2439	-0.0048	0.1110	0.1521	-1.3676	-0.0323	-0.8278	0.0650
Fe	-0.96	0.87	-0.98	0.43	0.5037	-0.0136	0.1425	0.3849	-0.4332	-0.0704	0.1067	0.0269
Ni	-0.86	0.99	-0.95	0.61	0.0298	-0.0009	0.0035	0.0329	-3.5080	-0.0748	-2.9682	0.0225
Pb	-0.18	-0.30	-0.21	0.71	0.0348	-0.0003	0.0337	-0.0159	-3.5630	-0.0099	-3.0232	0.0874
Zn	-0.73	0.31	-0.83	0.67	0.0127	-0.0002	0.0074	0.0032	-4.2606	-0.0372	-3.7208	0.0602
Cd	-0.89	0.99	-0.99	0.53	0.0025	-0.0001	0.0004	0.0026	-5.8618	-0.0741	-5.3220	0.0233
Al	-0.94	0.95	-0.98	0.87	0.0654	-0.0012	0.0322	0.0382	-2.7081	-0.0272	-0.8278	0.0650

TABLE 18: DRY DEPOSITION OF INCO EMISSIONS (r = 40 Km)

Parameters	NN*	N*	Daily Emissions (Kg)	Dry Deposition (Kg)	Prorated Dry Deposition** (Kg)	% Deposited	Background Deposition (Kg)	% Total+
SO_2	65	122	2,333,548	5,794	3,975	.17	10,427++	28
SO_4	116	315	49,067	54	37	.08	400	8.5
S	-	-	1,183,130	2,915	2,000	.17	5,347	27
Fe	97	274	1,626	406	279	17.2	1,277	18
Ni	91	265	798	56	38	4.8	11	78
Pb	97	269	480	1.1	.75	.16	4.1	15
Zn	96	273	126	.34	.23	.18	2.5	8.4
Cd	95	271	37	0.01	.007	.02	.15	4.5
Al	95	269	406	43	30	7.4	523	5.4

* NN = Number of days included in calculations; N = number of samples

** Prorated by the fraction of sampling days with impingement, factor = 0.686 (See text)

\+ INCO deposition / (INCO deposition + Background Deposition)

++ Based on an average background concentration of 8 ug m^{-3}

TABLE 19: DRY DEPOSITION OF FALCONBRIDGE EMISSIONS
(r = 40 Km)

Parameter	NN*	N*	Daily Emissions (Kg)	Dry Deposition (Kg)	Prorated Dry ** Deposition (Kg)	% Deposited	Background Deposition (Kg)	% Total+
SO_2	49	83	289,383	5,088	3,185	1.1	10,427++	23
SO_4	132	319	4,668	30	19	.41	238	7.4
S	-	-	146,248	2,554	1,599	1.1	5,293	23
Fe	107	269	100	224	140	140	1,095	11
Ni	107	270	14	12	7.5	54	11.3	40
Pb	108	270	37	2.3	1.4	3.8	5.0	22
Zn	108	272	5.7	0.2	.13	.23	3.2	3.9
Cd	108	270	12	0.01	.006	.05	.15	3.9
Al	66	174	32	24	15	47	416	3.5

* NN = number of days included in calculations; N = number of samples

** Prorated by the fraction of sampling days with impingement, factor = 0.626 (See Text)

\+ Falconbridge deposition / (Falconbridge deposition + Background Deposition)

++ Based on an average background concentration of 8 ug m^{-3}

Table A1: SES HiVol Network Performance Summary
(*included as an improper sampling day)

	Ash Street	Burwash	Lake Panache	McFarlane Lake	Wanup	Happy Valley	Markstay	Moonlight Beach
Total Number of Sampling Days	239	239	239	239	239	239	239	239
Number of Days with Improper Sampling	37	40	34	46	72	66	17	77
Number of Days with Passive Sampling*	8	6	2	16	19	24	4	31
Number of Days with No Filter Submitted*	1	1	8	4	9	6	1	8
Frequency of Problems (see Table 4 for Legend)								
Problem				Frequency				
1					12	6		2
2	1	1	6					
3				9				
4	7	9	8	9	7	2	4	6
5	1	6	7	1				
6					4	7		
7	2		2	1	3	1	2	2
8					4	5		4
9	3	1		6	3		1	
10						1		1
11						2		
12	1						1	
13	1	2		10	6	3	2	19
14					6	11	1	14
15			1			2		1
16	6	6	4	7	26	22	4	22
17	13	12	6		3		2	3
18	1		1			1		1
19		1						
20	10	10	7	12	12	13	9	8
21	1	1	1	1	1	1	1	
22	1				5	2	2	1

TABLE A2: Comments Legend for Table A1

1. Digital timer shut down early.
2. Unable to pick up sample due to weather conditions.
3. Mechanical timer shut down early.
4. Motor problem or breakdown.
5. Mechanical timer did not shut off.
6. Digital timer flashing through the day.
7. Human error (time not set properly, cassette not placed properly, chart box unplugged, torn filter).
8. Digital timer did not come on.
9. Mechanical timer did not shut off.
10. Digital timer did not shut off.
11. No equipment available for replacement of broken equipment (timers).
12. Mechanical timer did not come on.
13. Power failure.
14. Digital timer malfunction.
15. Chart recorder not working.
16. HiVol did not run for full time period, (cause unspecified).
17. Low volume flow rate.
18. HiVol ran for longer than required time period (cause unspecified).
19. Vandalism.
20. AccuVol not working properly.
21. Longer than normal passive period.
22. Unspecified problem.

TABLE A3: Total Ambient Air Concentration (ug m^{-3}) At Ash Street by Andersen Sampling

	1200h 1000h Aug. 2-Aug. 9 1978	0940h 1120h Mar. 29-Apr. 5 1979	0910h 0815h Aug. 16-Aug 23 1979	1600h 1140h Feb. 26-Mar. 4. 1980
Fe	.340	.314	.593	.201
Cu	.049	.020	.257	.221
Ni	.018	.005	.098	.042
Pb	.008	.139	.176	.128
Zn	(<.020)	.073	.116	.111
Al	.132	.158	.176	.044
Cr	-	<.002	<.005	-
Cd	.001	.001	.004	<.003
Mn	-	.008	.011	.004
Co	-	-	<.005	-
Mg	.109	.117	.119	.048
$N\text{-}NO_3$	-	-	-	-
SO_4	3.91	3.16	4.88	5.82
$N\text{-}NH_4$	-	-	1.31	-
Ca	.174	.126	.127	-
As	-	.002	-	-
Se	-	(<.001)	-	-

Table A4: Total Ambient Air Concentration (ug/m^{-3}) at Burwash by Andersen Sampling

	1100h 1400h Aug. 2 - Aug 9 1978	1045h 1015h Mar. 29 - Apr. 5 1979	1258h 1037h Aug. 23-Aug. 30 1979	1515h 1010h Feb. 26-Mar. 4. 1980
Fe	<.160	.079	.092	.064
Cu	.006	.009	.007	.008
Ni	-	(<.002)	<.004	(<.004)
Pb	-	.045	.068	.046
Zn	.010	.028	.026	.014
Al	17.79(?)	.079	.081	.065
Cr	-	-	(<.004)	(<.004)
Cd	-	.001	.001	.001
Mn	<.190	.002	.006	.004
Co	4.74×10^{-4}	-	-	-
Mg	4.11×10^{-3}	<.068	.050	.047
$N\text{-}NO_3$	-	-	-	.150
SO_4	-	2.63	9.25	2.70
$N\text{-}NH_4$	-	-	1.86	-
Ca	<94.43(?)	.062	.050	-
Ae	1.96×10^{-3}	.003	-	-
Se	$<7.0 \times 10^{-4}$	.001	-	-

Table A5: Total Ambient Air Concentration (ug m^{-3}) at Happy Valley by Andersen Sampling

	1700h Aug. 21 - 1800h Aug 27 1978	1400h Apr. 3 - 0950h Apr. 12 1979	1330h Aug. 16 - 0850h Aug 23 1979	1715h Mar. 4 - 1535h Mar 11 1980
Fe	.239	.659	.261	.051
Cu	.027	.028	.048	.041
Ni	.010	.023	.013	.011
Pb	.044	.062	.039	.020
Zn	.015	.044	.226	-
Al	.207	.146	.168	.020
Cr	-	(<.0017)	-	-
Cd	.002	.004	.002	<.007
Mn	-	.005	.005	(<.004)
Co	-	(<.0023)	-	-
Mg	.062	.102	.108	.008
$N\text{-}NO_3$	-	-	-	.120
SO_4	5.46	3.19	4.17	1.54
$N\text{-}NH_4$	-	-	1.02	-
Ca	.067	.199	.066	-
As	-	.023	-	-
Se	-	.001	-	-

Table A6: Total Ambient Air Concentration (ug m^{-3}) at Lake Penage by Andersen Sampling

	1010h Aug. 10 - Aug 16 1120h 1978	1600h Apr. 5 - Apr. 12 1125h 1979	1415h Aug. 16 - Aug. 23 1215h 1979	1345h Mar. 4 - Mar. 11 1420h 1980
Fe	.393	.103	.088	.034
Cu	.065	.012	.010	.021
Ni	.005	<.002	<.004	.004
Pb	.067	.029	.035	.037
Zn	<.024	.102	.032	.015
Al	.122	.063	.170	.082
Cr	-	-	-	-
Cd	.001	.001	.001	.001
Mn	-	-	.004	<.003
Co	-	-	-	-
Mg	.115	-	.084	.021
$N\text{-}NO_3$	-	-	-	.159
SO_4	11.91	2.53	8.51	4.30
$N\text{-}NH_4$	-	-	1.52	-
Ca	.173	<.038	.048	-
As	-	.005	-	-
Se	-	-	-	-

Table A7: Summary of Mass Median Diameters and Deposition Velocities
(MMD Values Correspond to Measurements at Ash Street, Burwash, Happy Valley, and Lake Penage)

	Summer Aug/78 MMD	Av	V_d	Winter Apr/79 MMD	Av	V_d	Summer Aug/79 MMD	Av	V_d	Winter Mar/80 MMD	Av	V_d
Fe	8.0, 3.5, 9.0, 6.0	7.1	1.4	7.2, 6.0, 7.4, 5.5	6.5	1.35	9.0, 4.0, 7.0, 2.7	5.7	1.2	9.0, 2.6, 5.0, 2.1	4.7	.98
Cu	3.8, 2.8, 7.4, 2.3	4.1	.7	3.0, 2.6, 5.4, 2.0	3.3	.5	8.0, 4.0, 2.7, 1.6	4.1	.7	1.15, 2.0, 2.2, 1.5	1.7	.06
Ni	>9.0, -,>9.0,>9.0	>9	-	7.0, -,9.0, 1.7	-	-	8.2, - 6.2, -	7.2	1.4	6.4, - 8.0, 2.4	5.6	1.2
Pb	1.1, -, 3.3,* 0.7	.9	.03	0.7, 1.1, 1.5, 1.4	1.2	.035	0.36, 0.68, 0.84, 0.8	.7	.025	0.56, 0.44, 0.42, 0.55	.5	.021
Zn	0.4, 0.64, 7.2	.52	.022	<0.4, 1.1, 1.7, 0.4	8	0.26	<0.4, 0.79, 0.4, 0.79	.5	.021	1.1, 0.92,<0.4, 0.7	.7	.025
Mn	-, 3.9, -, -	3.9	.65	4.7, 3.7, 0.68, -	4.2	.82	2.3, 2.3, 0.36, 1.55	2.05	.14	2.6, 1.6, -, -	2.1	.14
Al	>9.0, 5.3,>9.0, 8.0	-	-	6.0, 3.8, 5.5, 4.0	5.3	1.1	7.4, 4.2, 3.3,<0.4	5.63	1.2	6.6, 3.5, 2.5, 1.1	3.4	.53
Cd	3.0, - 1.6,>9.0	-	-	1.9, 1.15, 1.1, 1.05	1.3	.09	0.64, 1.3, 0.84, 0.76	0.9	.03	0.60, 2.3, 0.66, 0.90	1.2	.035
Ca	7.4, 6.6,>9.0, 9.0	-	-	7.0, 6.0, 6.5, 3.4	5.7	1.2	6.4, 1.7, 2.1, 3.2	3.4	.33	-, -, -, -	-	-
Cr	-	-	-	2.8	2.8	.30	-	-		-	-	
Mg	6.9, 6.0, 9.0, 8.4	7.6	1.5	6.2, - 6.2, -	6.2	1.3	7.4, 0.8, 3.1,<0.4	5.3	1.05	4.2, 2.6, 0.41 1.9	2.9	.32
As	-, 0.55, - , -	0.55	.022	1.0, 1.15, 0.85, 0.9	1.0	.033	-, -, -, -	-		-, -, -, -	-	
Se	-, 0.68, -, -	.7	.025	1.0, 1.35, 0.9, -	1.1	.034	-, -, -, -	-		-, -, -, -	-	
SO_4	0.55,-, 2.0, 0.64	1.1	.034	0.66, 0.84, 0.8, 0.90	.8	.027	0.56, 1.1, 0.52, 0.9	.8	.027	0.68, 0.64, 0.4, 0.54	.5	.021
NH_4	-	-		-	-		0.57, 0.98, 0.65, 0.89	.8	.027	-	-	
NO_3	-	-		-		-		-		<0.4,<0.4,<0.4, 0.58	.3	.02
Co	-, 4.5											
Cl	-, 4.0											
Rb	-, 1.7											
Sb	-, 2.2											
Tl	-, 3.3											
Sm	-, 4.7											
Na	-, 3.5											
Au	-, 1.5											
La	-, 4.8											
Sc	-, 6.0											
V	-, 1.9											

* underlined values are suspicious and are not included in calculations.

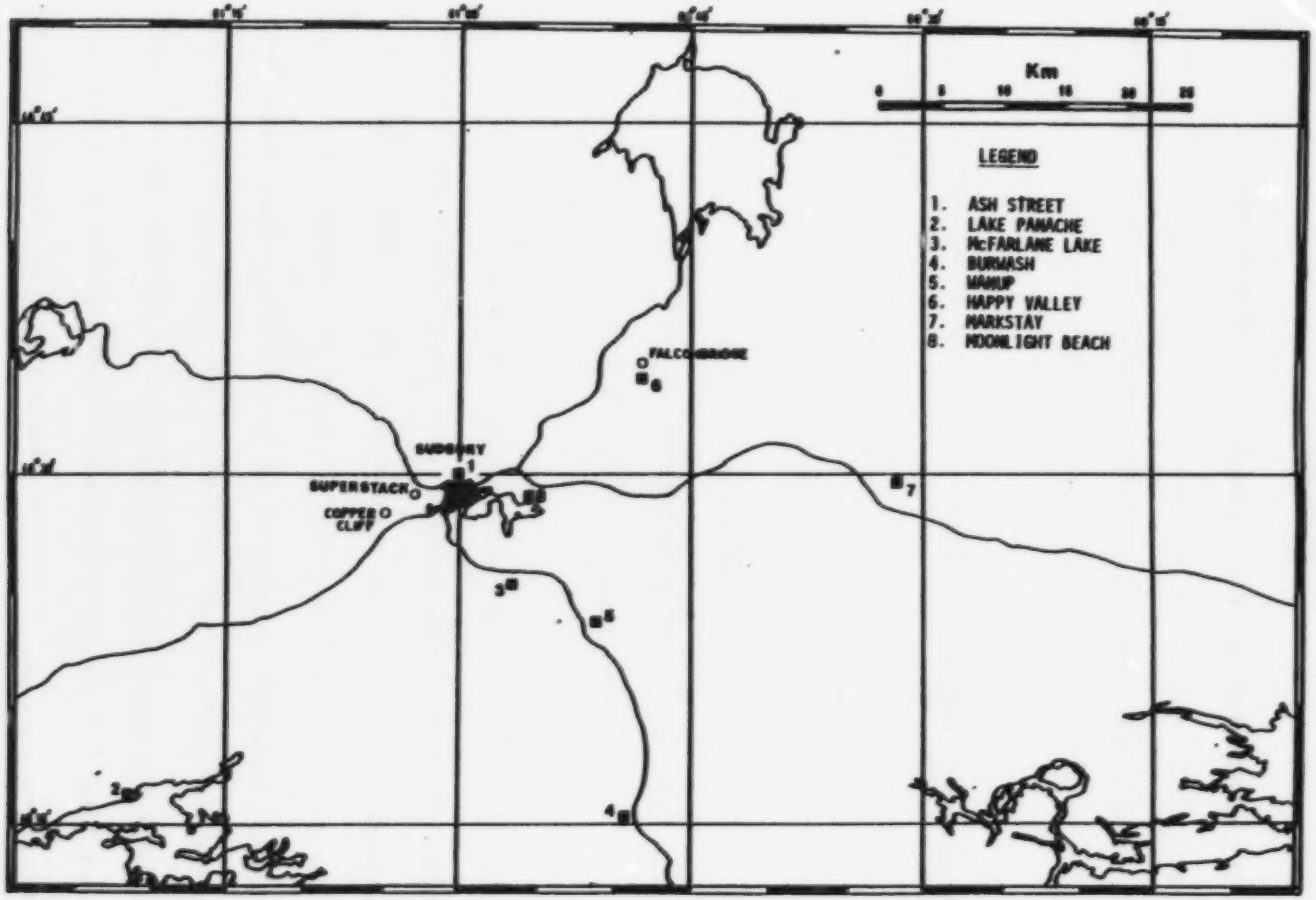

FIGURE 1: SES HIVOL SAMPLING NETWORK

APPENDIX 1

SES HIVOL NETWORK DESIGN AND OPERATION

APPENDIX I

A1.1 Design

The HiVol Sampling Program was designed primarily to fulfill the first objective, i.e. to quantify the contribution of local smelter emissions to the dry deposition field in Sudbury. Fulfillment of the remaining objectives followed automatically.

The relationship between dry deposition and HiVol sampling results is given by:

$$D = V_d C \qquad (1)$$

where D = deposition ($ug/m^2/day$)

V_d = deposition velocity (m/day)

C = ambient air concentration (ug/m^3) at some reference height for the pollutant of interest

Equation 1 states that the dry deposition flux of a pollutant to a surface is proportional to the ambient air concentration of the pollutant; the proportionality constant is assumed to be constant and representative of an average velocity with which the pollutant flows to the surface. This relationship is a simplification of the complicated deposition mechanisms which occur naturally in the atmosphere. For instance, the deposition velocity is not constant but varies significantly depending on the nature of the surface, the atmospheric turbulence structure, the flow field, the size of the pollutants (if in particulate form) and the nature of the pollutant. Several recent publications (5, 8, 17) provide a detailed description of these mechanisms.

Notwithstanding the simplifications, the deposition velocity approach is generally accepted as the best method currently available for the determination of long-term dry deposition values (18). The HiVol program in Sudbury was based on this acceptance and was designed so that the HiVol sampling provided the necessary concentration data and from the Andersen experiments the appropriate particle size information, for deposition velocity estimates.

The HiVol network consisted of eight sampling sites . The distance of the individual sites from the major smelter sources (INCO and Falconbridge) varied from 2 Km to 52 Km. Six of the eight were located in the quadrant southeast of the two smelter sources in Sudbury. This quadrant was chosen because it was in the dominant flow direction of source emissions, and had good road accessibility and relatively good sampling site. The sites chosen were Burwash, Happy Valley, Markstay, McFarlane Lake, Moonlight Beach and Wanup. The actual locations are shown in Figure 1.

Of the two remaining sites, one (Panache) was located to the southwest of the sources and was considered as a background monitoring site for many of the events. This was confirmed by the Northeastern Region SO_2 measurements, which showed very little impingement of local plumes at this site (19).

The last site (Ash Street) was located within the city of Sudbury. It was chosen to measure the influence of both the smelter emissions and the urban area on local air quality.

An essential part of the overall design of the HiVol Program was the HiVol stratification scheme, whereby HiVol samples were separated into plume-affected and background sets and only samples collected on days with evidence of plume impingement at or near the HiVol samplers were submitted for laboratory analysis (with the exception of Panache and Ash Street samples which were all submitted for analysis). The use of this scheme allowed the program to operate with eight samplers with a budget insufficient to carry out laboratory analysis of all samples.

A three day per week sampling schedule was chosen with Sundays, Tuesdays and Thursdays as the principal sampling days. Twenty-four (24) hour sampling was done from 0000 to 2400 hours EST.

A1.2 Instrumentation

A1.2.1 HiVol Sampler

The General Metal Works Model GMWL 2000H High Volume Air Sampling System was the basic instrument used in the HiVol program. It consisted of a stainless steel filter holder, a pressure transducer/recorder, a volume controller, a Model GMW-70 seven day timer, a standard blower/motor assembly, and a standard 132 cm high aluminum shelter. Mid-way through the program, Moore and Gentry Model 430/450 electronic timer/airflow controllers were used in three HiVol samplers. These units were plagued by poor performance and accounted for a good portion of the lost data in the program.

The HiVol samplers were operated at 40 to 60 cfm with typical variations of ± 10 cfm. All filters were pre-loaded in GMW-3000 Filter Paper Cartridges prior to installation in the sampler.

Calibration for the samplers was carried out at least once per month as well as at each time a component was changed in the sampler. A Sierra Instruments HiVol Calibration Plate and a U-tube manometer were used for the calibration.

Throughout the entire course of the HiVol Program, Whatman 41 cellulose filters (20.3 cm x 25.4 cm) were used as the filter medium. The low metals background, the lack of spurious sulfate formation and the high collection efficiency for most of the parameters of interest made this filter the most suitable for use in the Sudbury Study. A detailed description of the rationale for using this filter medium is given elsewhere (2).

A1.2.2 Hivol Exhaust Contamination

Several workers (3) have suggested that contamination of HiVol filter samples by copper can occur due to removal of Cu from the motor commutator and the subsequent re-entrainment of the exhaust into the air sample stream. An initial inspection of the SES HiVol data revealed that the copper concentrations in the APM were high relative to those of nickel, in view of the emission rates of the two. Several experiments were designed to assess whether contamination could occur with species of interest other than copper. This was done by collecting motor exhaust on filter paper using a lo-vol sampling method. These

experiments showed that copper was by far one of the largest exhaust contaminants, and that errors in the other paramenters of interest to this study should be very small - a conclusion supported by other studies (20).

A1.3 Operations

Network operations are described under the following headings -siting, filter handling, and sampler operation.

A1.3.1 Siting

The siting criteria for the network were as follows:

a. The site should be relatively open with a clear fetch in the direction of Sudbury.

b. The site should be roughly 100 m from roads (preferably paved) with no salt piles, sand piles, cultivated fields or sandy areas in the immediate vicinity.

c. Power, easy access and safety must be available year round.

Because of the nature of the Sudbury area, it was not possible to satisfy all of these criteria for every site. The sites which were chosen were felt to be the best available in the entire area. A brief description of the individual sites is given below:

1. Burwash

Burwash was considered to be the best site of the eight. It was located on the former site of the Burwash Industrial Farm roughly 30 Km SSE of the INCO 381 m chimney. The sampler was located at ground level in an open grassy area. A paved access road was located roughly 50 m north of the sampler and Highway 17 was located roughly 150 m east of the sampler.

2. Wanup

The Wanup sampler was located on the roof of a small building roughly 3m above ground level. This provided a clear fetch in the direction of Sudbury. A lightly travelled road was located roughly 50 m west of the sampler. The site was approximately 20 km to the SE of the INCO 381 m chimney.

3. McFarlane Lake

The sampler at McFarlane Lake was set in a large cleared area roughly 100 m behind several Government of Ontario buildings. A paved parking lot existed about 50 m to the north of the sampler. The entire area was grass-covered and the HiVol was positioned at ground level. The site was located roughly 9 Km SE of the INCO 381 m chimney.

4. Moonlight Beach

The Moonlight Beach sampler was located on the rooftop of building roughly 4m above ground level. The entire area was clear and grassy with some open sand. In the winter this site was accessible only on snowshoes. It was located 10 Km east of the INCO 381 m chimney.

5. Happy Valley

The site at Happy Valley was located in a large open area 2 Km due south of the Falconbridge Nickel Mines smelter in Falconbridge and 20.5 Km NE of the INCO smelter. It was located on the roof of an SO_2 monitoring station in a valley approximately 20 m below the smelter complex, and a high frequency of Falconbridge plume impingements was observed at this site. It should be noted that the area surrounding the sampler is largely bare and sandy, and hence this was perhaps the poorest HiVol site in the SES network.

6. Markstay

The Markstay HiVol was located south of the town of Markstay roughly 38 Km due east of the INCO 381 m chimney. It was located in a grassy clearing on private property.

7. Ash Street

The Ash Street site was located on the west side of the City of Sudbury, 3.5 Km ENE of the INCO 381 m chimney. It was set on a hill with a considerable amount of bare rock exposed on the surface. The sampler was located on the roof of the Northeastern Region's Air Pollution Index station. A lightly - travelled access road ran past the site roughly 20 m from the sampler and the entire site was located at the base of a municipal water tank.

8. Lake Panache

The Lake Panache site was generally found to be the background monitoring site for the network. It was co-located with a Northeastern Region SO_2 monitor which indicated that plume impingements from the Sudbury were relatively infrequent compared to

other directions. The site was located 32 Km SW of the INCO 381 chimney. The ground cover was grassy and the sampler was set at ground level in a small clearing on the edge of Lake Panache.

A1.3.2 Filter Handling

Throughout the entire HiVol program sampling was carried out from 0000 to 2400 hours local time on Tuesdays, Thursdays and Sundays. Filter changes were done on Wednesdays, Fridays and Mondays during working hours. As a result, filters were exposed passively for 8 to 16 hours before and after the actual sampling times on Tuesdays and Thursdays and an extra 24 hours before the Sunday sampling.

Prior to installation in the high volume sampler, the Whatman 41 filters were mounted in pre-cleaned filter cartridges. Disposable gloves and teflon-coated tweezers were used during this operation and it was done at the Sudbury Environmental Study Laboratory on Kelly Lake Road.

The eight loaded cartridges were then taken to the field in a specially constructed carrying case. At each site the exposed filter cassette was removed and replaced with the unexposed cartridge. The HiVol sampler was then checked for proper operation, the timer was reset and the flow recording chart was removed and replaced. Filter handling and servicing at the eight samplers required approximately a full day (depending on the weather conditions) and required a 265 Km round trip.

On returning to the field laboratory the filters were removed from the cartridges - again using plastic gloves and tweezers. They were

then inserted in individual filter submission envelopes, flow volumes were calculated and laboratory submission forms were filled out.

Each week, the filters were sent to the Laboratory Services Branch (LSB) of the Ministry of the Environment. All samples were analyzed for SO_4, NO_3 and NH_4 on receipt. Only the Ash Street and Lake Panache filters were also analysed for trace metals. The remaining filters were stored at LSB until the HiVol stratification scheme was completed and a list of filters requiring metals analysis was forwarded to the laboratory. For reasons described later, the time between exposure and analysis of these filters was typically four months.

In January 1980, the system was changed such that all filters submitted for analysis were analysed immediately. This was done to reduce the delay time between submission and data analysis as the end of the program approached.

A1.3.3 Network Performance

Table A1 summarizes the performance of the HiVol network. It can be seen that the total number of sampling days for all stations was 239 and the number of days of lost samples varied from station to station, with a minimum of 17 and a maximum of 72. These numbers are somewhat misleading, because a good deal of the lost samples occurred in the first two months of the program. The criteria for proper sampling were:

a) The sampling period was approximatly 24 hours from 0000 to 2400 hours.

b) The HiVol operated continuously throughout the period.

c) The flow rate lay between 40 and 60 cfm.

In some cases, the HiVol did not sample at all during the required period. Such filters were referred to as "passive" and provided the opportunity to assess the effects of dry deposition on the filter surfaces between sampling periods. All such filters were submitted to LSB for chemical analysis. Compared to the 24-hour samples at 40-60 cfm, the passive loadings were negligible.

The last column of Table A1 summarizes the type and frequency of problems related to improper filter exposure. When reviewing this column one should note that more than one comment often accompanied an improperly exposed filter.

The data in this column indicate quite clearly that the three digital timer/flow controllers performed very poorly compared to the mechanical timer/volume controller units. The three digital units were located at Wanup, Happy Valley and Moonlight Beach. While attempts were made to alleviate the problems with these instruments, they still do not operate as well as desired - especially during the winter months.

The operation of the samplers at the other 5 sites was good with only 7 to 19% of the filters not exposed properly.

A1.4 Chemical Analysis

All chemical analyses were carried out by the Laboratory Services Branch in Rexdale. At the beginning of the Network operation,

the non-metal inorganic species (SO_4 and NO_3) were analyzed by autoanalyzer techniques and the trace metals by flame atomic spectrometry. As of April, 1979, SO_4 and NO_3 were analyzed by ion-exchange chromatography techniques, NH_4 by the phenate hypochloride method and the trace metals by flameless atomic absorption. Typical detection limits associated with the various methods are given in Table 3. All results reported are corrected for filter blanks except in the case of $N\text{-}NH_4$ which filter blank values are highly variable and sometimes significant.

A1.5 Particle Sizing Experiments

A1.5.1 Introduction

The wet and dry deposition of particulate matter, be it locally emitted or transported into the area, depends strongly on the size distribution of these particulates (5, 8, 21). Therefore special experiments using Andersen low volume impactors were carried out to determine particulate sizes, and to obtain corresponding deposition velocities for deposition rate calculation purposes.

A1.5.2 Experimental

Two Andersen 2000 Inc. Model Mark II Cascade impactors were used in the experiments. Because of the loading requirements for chemical analysis, all samples were 7-day samples. Normally the air stream is drawn through a pre-separator followed by eight impaction stages before reaching the backup filter. The purpose of the pre-

separator is to reduce particle bounce and wall loss problems, which are mainly associated with large particles. Different types of filter substrates were used-teflon in the pre-separator, polyethylene on the 8 stages, and Whatman 40 as the back-up filter. Due to chemical analysis problems associated with the teflon substrates, the pre-separator was used only in the August, 1978 study and not in any of the subsequent studies. The 50% effective cut-off aerodynamic mass median diameters (MMD) of the various stages are from 9.0 um to less than 0.4 um. A small amount of ethanol was used to help keep the substrate in contact with the stage metal plate. A typical flow rate of 1 c.f.m was used.

Except for the sample set collected at Burwash in August 1978, which was analyzed by neutron activation analysis by Prof. A. Chatt of Dalhousie University (teflon pre-filters not analyzed for), all other sample sets were analyzed using ion-exchange chromatography and atomic absorption techniques, after proper chemical extractions. More details are given elsewhere (6,7).

A1.5.3 Sites and Sampling Periods

Four different sites were chosen for the reason that they were affected to a different extent by smelting operations, and had different site-specific characteristics (e.g. ground cover). Ash Street is located in the city of Sudbury, therefore APM is also affected by sources other than smelting operations such as traffic, home heating etc. Because of the proximity of INCO, it is frequently impacted by INCO low level emissions. Burwash occasionally experiences fumigation from the INCO 381 m chimney and is expected to have a relatively small wind blown dust

contribution due to the grassy ground cover. Happy Valley is expected to have a large wind blown dust contribution since there is little vegetation in the area. This location is frequently fumigated by the Falconbridge stack plume. Panache is relatively infrequently impacted by the smelting operations, and under normal conditions can be considered as a "background" station.

Experiments were planned to take place both in the summer (August 1978 and 1979) and winter (March 1979 and February 1980) periods, and under different smelter operating conditions which are summarized in Table 4. This consideration allowed sizing information to be obtained as a function of season and smelter operating conditions.

A1.3.4 Results and Discussion

The average ambient concentrations over a one week period at the four sites obtained during four different sampling periods are summarized in Tables A3 to A6.

The sizing data are graphically shown in Table A7 as aerodynamic mass median diameters. Based on the compilation of Dennison et al. (8) (refer to figure 4), the corresponding deposition velocities are estimated and are also given in Table A7.

By examining the concentration data obtained at the same site under different sampling conditions which included a wide range of

ground cover types as well as smelter shutdowns, it was found that most of the data from the different sampling periods were quite similar, suggesting that primarily background air, and not local plumes, were sampled. This is understandable, as the probability of a sampler being hit by the plume was small.

Similar observations were made of the sizing data, i.e. they did not seem to differ much under various sampling conditions. This, coupled with the concentration results, suggests that there is no obvious impact due to local sources on the ground based measurements. For this reason, a V_d value determined from the averaged ground-based measure ments was used for background particulate deposition rate calculations for each parameter while the combined particle size information (of the INCO 381 M chimney plume, Iron Ore Recovery Plant (IORP) Stack plume and the plume of the Falconbridge smelter stack) determined from the airborne studies (6,7) was used for local industrial source contribution calculations. These V_d values are tabulated in Table 5.

It should be pointed out that there is considerable uncertainty in the V_d values, especially for SO_4 - see, for example, Lusis and Shenfeld (12). This should be kept in wind when considering the dry deposition estimates in the present report.

APPENDIX 2

HIVOL SAMPLE STRATIFICATION SCHEME

APPENDIX 2

The HiVol stratification scheme was implemented as a method of reducing the number of HiVol filters requiring full chemical analysis, while still allowing the objective of the program to be fulfilled.

The method was designed to identify filter samples which were potentially affected by the local smelter emissions. These filters were then flagged for chemical analysis by the Laboratory Services Branch.

The stratification was done as follows:

1. For each day between June 1, 1978 and May 31, 1980, ground level SO_2 concentration data and upper level wind direction data were plotted on a map of the Sudbury area. The former data were obtained from the Northeastern Region's 16-station SO_2 monitoring network, and the latter from the Northeastern Region's 76 m-level anemometer located at Frood Road in Sudbury.

2. Each map was interpreted to determine the history of the local emissions during that day. The following information was extracted:

   - Which stations were impinged upon by local emissions?
   - Which local sources potentially affected which stations?
   - Was impingement certain, or just probable?
   - Which station measured background concentrations only?
   - What were the general flow directions during the day?

- Did the impingment episode persist longer than 12 hours?
- What was the amount and type of precipitation that fell during the day (at Sudbury airport)?
- Which filters required chemical analysis?

Determination of plume-effect at each HiVol station was done by assessing the SO_2 concentration field and the wind data. Additional information from plume observations (carried out daily by the Sudbury Environmental Study technical staff) as well as pilot balloon ascent data (9) were used to supplement the data whenever possible. Since the Panache, Happy Valley, Burwash and Ash Street HiVol stations had co-located SO_2 monitors, they were easy to assess for impingement. The other stations required some interpolation between existing SO_2 monitors, as well as a careful assessment of the wind field.

3. A list of all filters requiring full chemical analysis was prepared and forwarded to LSB. It was the general practice to include for analysis all 6 filters from the so-called "HiVol sector" when two or more stations were plume-affected. This provided some room for error in the stratification process, as well as data for the future evaluation of the success of the scheme.

Several points and observations related to the HiVol stratification scheme are of special note:

1. The time between filter exposure and laboratory analysis was

typically four to six months (except for Ash Street and Panache filters). This was due to the delays in processing the SO_2 monitoring data, in carrying out the stratification scheme, and laboratory analysis backlogs.

2. A particular source affecting a particular station was sometimes difficult to distinguish. For example, emissions from both INCO and Falconbridge often appeared to overlap within the HiVol sector. In such cases, both sources were cited as potentially affecting the HiVol stations. Only samples which could be assigned as background or being affected by the INCO or Falconbridge sources were used in the calculations.

3. INCO 381 m chimney emissions were considered separately from the INCO Iron Ore Recovery Plant (IORP) stack, and INCO low level emissions. This is because the height of the former essentially eliminated winter time impingement of the plume, because of plume trapping above upper level inversions.

4. The Panache site was seldom impinged upon by either INCO or Falconbridge emissions. The site proved to be excellent for background monitoring, and was generally quite representative of other non-affected sites on any given day.